

# **A fifty-year analysis of global ocean surface heat flux to improve the understanding of the role of the ocean in climate**

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## **1. PROJECT SUMMARY**

The ocean and the atmosphere exchange heat at their interface via a number of processes: solar radiation, longwave radiation, sensible heat transfer by conduction and convection, and latent heat transfer by evaporation of sea surface water. The amount of heat being exchanged is called heat flux. The distribution of heat flux over the global oceans is a key element for climate studies, as it is required to establish air-sea feedback mechanisms, to provide guidance and motivation for modeling studies, to verify individual or coupled atmosphere-ocean general circulation model simulations, and to serve as forcing functions for ocean model exercises. However, direct flux measurements are sparse. Our present knowledge of the global air-sea heat flux distribution stems primarily from the bulk parameterizations of air-sea fluxes as functions of surface meteorological variables (e.g., wind speed, temperature, humidity, cloud cover, etc). The source of observations for those flux-related variables include marine surface weather reports from Voluntary Observing Ships (VOS) collected by Comprehensive Ocean-Atmosphere Data Set (COADS) and satellite remote sensing from various platforms. Atmospheric reanalyses from numerical weather prediction (NWP) centers such as National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) provide additional model-based database. Nonetheless, none of the three data sources are perfect as each suffers from at least one of the four deficiencies: (1) incomplete global coverage, (2) relatively short time series, (3) systematic bias, and (4) random error.

While improving the quality of each data source is a necessary step toward improving the estimates of surface heat fluxes, this project takes an alternative approach, i.e., to improve the quality of the flux estimates through objectively synthesizing the advantages of the three data sources. The synthesis approach has been applied successfully to generate gridded products of surface vector wind, SST, and precipitation. This project, which is termed “Objectively Analyzed air-sea heat Fluxes (OAFlux)”, develops an equivalent global synthesis product for surface heat fluxes by utilizing the methodology developed and experience learned from a previous pilot study for the Atlantic Ocean.

The project has two main objectives. The first objective is to produce a 50-year (from the mid 1950s onward) analysis of surface latent, sensible, net shortwave and net longwave radiation fluxes over the global oceans with improved accuracy. This will be achieved by an appropriate combination of COADS data, NWP reanalysis output, and satellite retrievals using advanced objective analysis. The target resolution is 1° longitude by 1° latitude and monthly. Daily flux fields are produced when satellite data are available. The second objective is to use the data to study the heat flux variability on seasonal, annual, interannual, decadal and longer timescales and their relation to global climate change. The scientific investigation helps to assess the quality and reliability of the dataset in depicting the multi-decade climate record since the 1950s and to provide physical insights into the dataset.

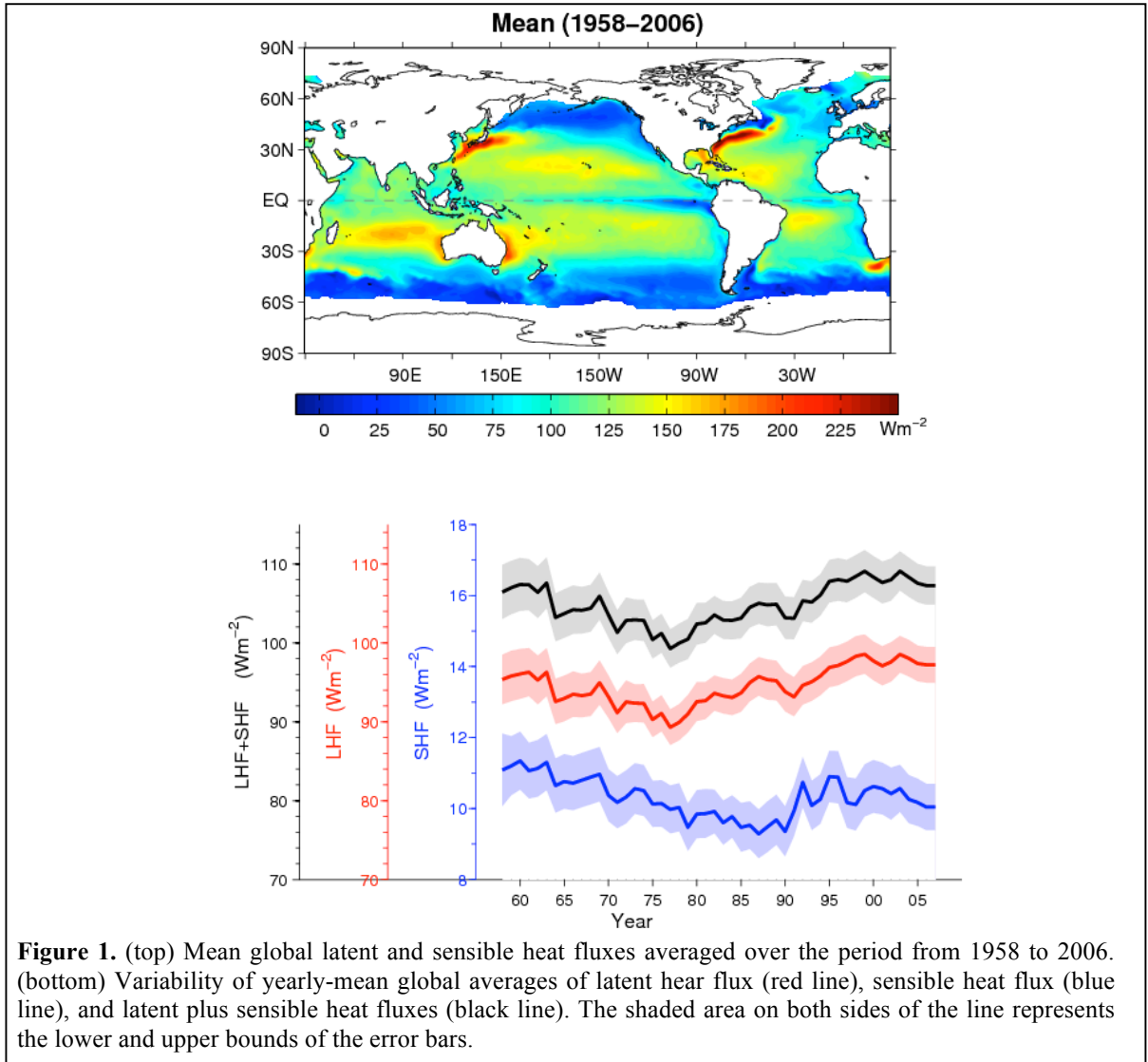
Global analysis of global air-sea latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables has been completed for the years 1958–2006 with monthly and daily resolutions. The datasets are freely available to the community via the project website (<http://oaflux.whoi.edu>). The proposed study contributes to the CLIVAR programs including CLIVAR Atlantic, Pacific and PACS, and benefits the CLIVAR and other research communities on studies of climate variability and predictability.

## **2. ACCOMPLISHMENTS**

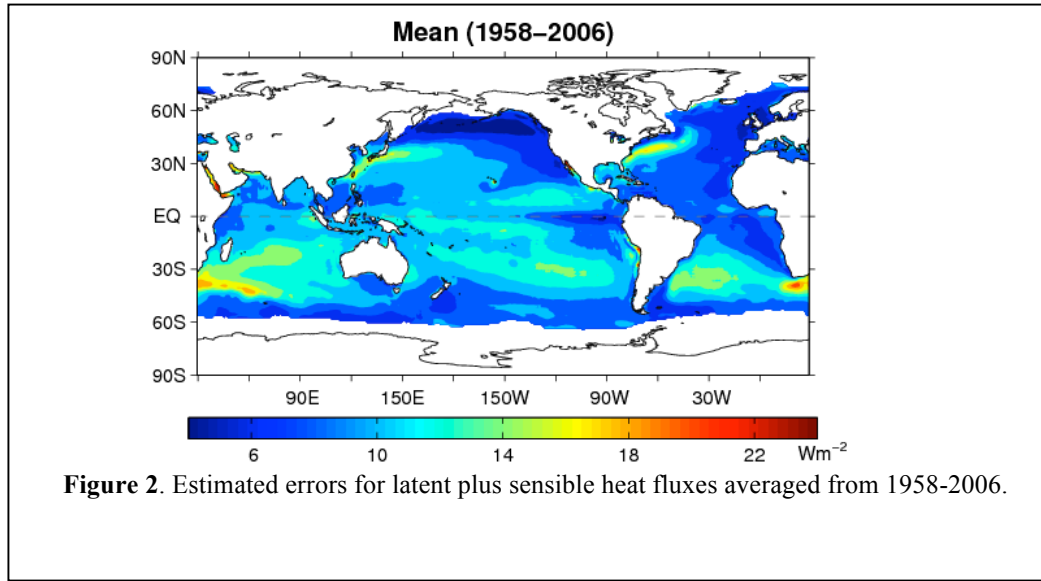
The major tasks that have been carried out in FY2008 include:

### **2.1. Public release of OAFlux analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006**

The OAFlux project announced the release of the third version of OAFlux products in early 2008. The version consists of a global analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006 on 1-degree resolution, with monthly datasets available for the entire 49-year period and daily datasets from 1985 onward (Figure 1). The project has made two releases before: one was in March 2004 for the Atlantic Ocean basin analysis (1988-1999) and the other was in December 2005 for the global ocean analysis (1981-2002).



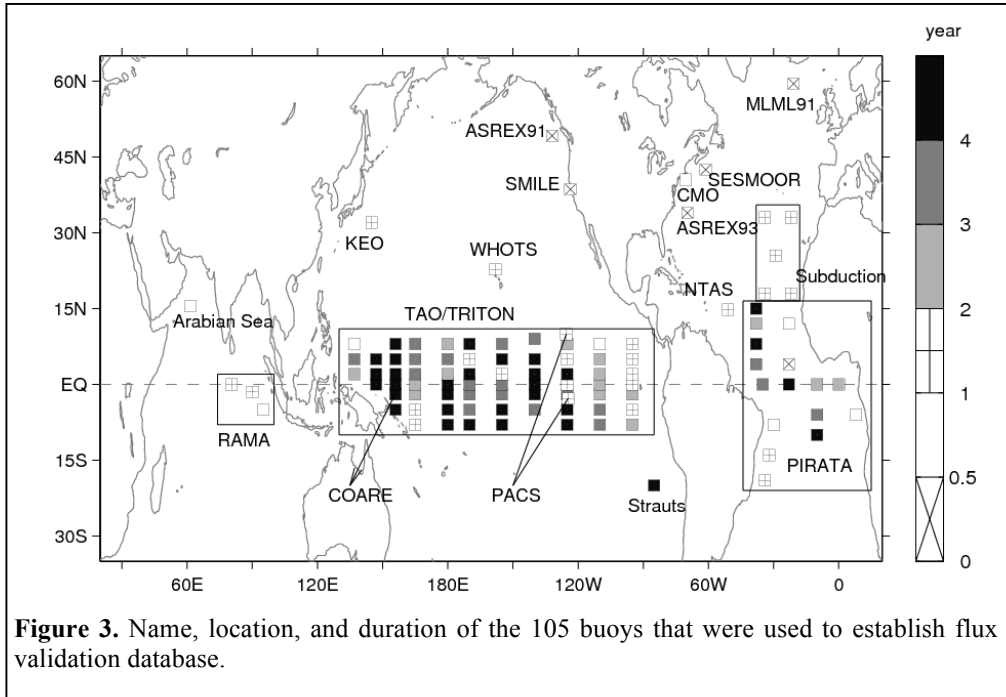
The OAFlux products are constructed not from a single data source, but from an optimal blending of a total of 22 daily input fields originating from three NWP reanalyses (ERA40, MCEP1, NCEP2) and multiple satellite platforms (AVHRR, SSM/I, QuikSCAT, AMSR-E). These optimally estimated daily surface meteorological fields were then input into the COARE bulk flux algorithm 3.0 to compute daily flux fields. Methodology, strategy, and procedure of the synthesis were detailed in a technical report ([1] Yu et al. 2008). Also discussed in the report is the accuracy of the flux estimates. The OAFlux daily time series were compared with in situ flux time series measurements at 107 locations (105 buoys plus 2 ships) over the global basin to assess the accuracy of the estimates. The comparison shows that daily latent plus sensible heat flux estimates are unbiased and have the smallest mean error: the mean OAFlux-buoy difference is of  $1.0 \text{ Wm}^{-2}$  and the mean OAFlux-buoy difference in absolute measure is of  $7.4 \text{ Wm}^{-2}$ . Based on the buoy comparisons, error estimation for daily global flux field was derived through post analysis (Figure 2).



The datasets are freely available to interested users for non-commercial scientific research through the project website at <http://oaflux.whoi.edu/>. The data are also archived at two data centers outside WHOI: one is the Asia-Pacific DATA-Research Center (ADPRC) at the University of Hawaii ([http://apdrc.soest.hawaii.edu/w\\_data/air-sea3.htm](http://apdrc.soest.hawaii.edu/w_data/air-sea3.htm)), and the other is the Data Support Section (DSS) at NCAR (<http://dss.ucar.edu/datasets/ds260.1/>).

## **2.2. Construction of flux validation database that constitutes flux buoy time series measurements at 100+ locations**

*In situ* air-sea time series measurements from surface moored buoys have been a useful reference for validating flux estimates derived from ship reports, satellite observations, and NWP models. They are regarded as ground-truth and can help identify system biases in gridded flux products and quantify error and uncertainty. Recognizing the important role of flux buoy measurements in developing improved global flux products, efforts have been made to collect all available air-sea time series measurements from flux buoys over the global basins and to compile them all to establish a flux validation database. A total of 105 flux buoys was collected (Figure 3), among which only 62 locations were equipped with pyranometers (downward shortwave measurements) and 24 locations with pyrgeometers (downward longwave measurements) at 24 buoy locations. The database is a key validation tool in developing OAFlex products ([2] Yu et al. 2008).

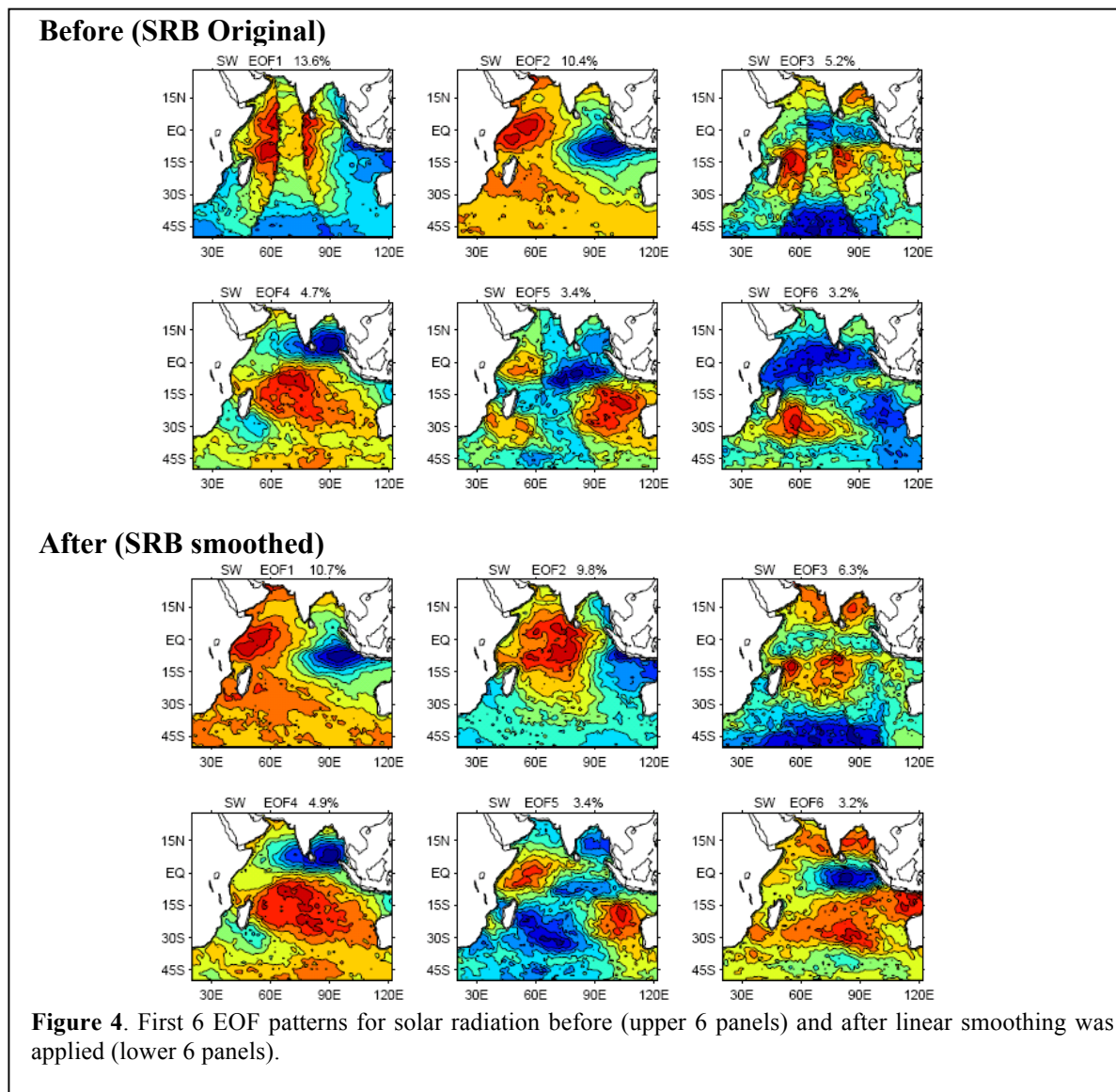


### 2.3. Experimenting optimal approaches to improve estimates of shortwave and longwave radiation at the ocean surface

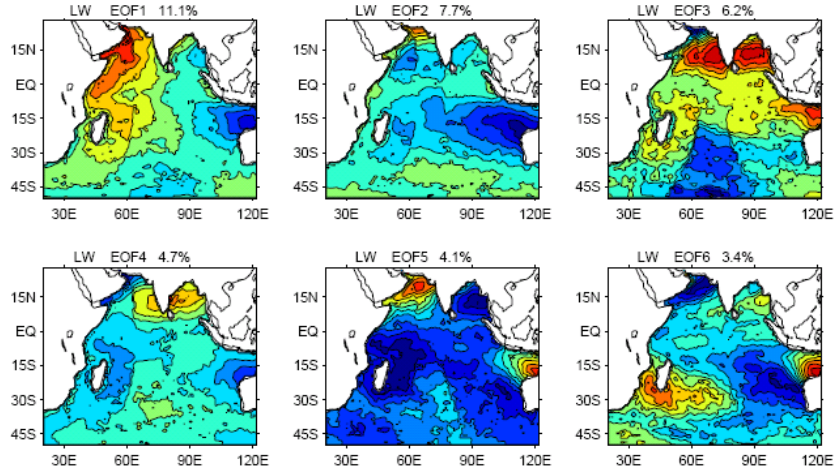
Incoming solar radiation ( $Q_{SW}$ ) is the only significant external heat source at the ocean surface. Its balance with ocean heat loss processes (e.g. longwave radiation ( $Q_{LW}$ ), latent heat ( $Q_{LH}$ ) and sensible heat ( $Q_{SH}$ ) losses) drives the ocean meridional heat transport and attenuates temperature contrasts between equator and poles. To understand and explain past and current climate conditions and to predict future climate conditions, we need to know how solar and longwave radiation components have been changing, how the change affects the net heat balance (i.e.,  $Q_{net} = Q_{SW} - Q_{LW} - Q_{LH} - Q_{SH}$ ), and how  $Q_{net}$  is related to the warming of global oceans.

After completion of the ~50-year global analysis of air-sea latent and sensible heat fluxes, the technical focus of the OAFlux project has moved on to improving radiation estimates at the ocean surface. Two data sets are used, one is the International Satellite Cloud Climatological Project (ISCCP) and the other is from the NASA/GEWEX Surface Radiation Budget (SRB). Extensive comparison with in situ flux buoy measurements has been conducted, from which three major biases/errors in these two products are identified. The first one is the so-called “Indian Ocean Gap” (Figure 4), due to the lack of coverage from geostationary satellites over an area centered on 70°E for all of the July 1983 - June 1998 time period. The gap was eliminated after June 1998 when Meteosat-5 was moved over the region. The second is the large overestimation of ISCCP incoming solar radiation in the equatorial oceans. ISCCP is severely biased, with the largest bias ( $>30\text{Wm}^{-2}$ ) over the western tropical Pacific and eastern Indian warm water regions. SRB also overestimates solar radiation but with lesser degree. The third problem is the spurious jumps in the time series of global averaged longwave radiation in ISCCP datasets, caused by spuriousness in atmospheric temperature products from the NOAA operational TOVS. These three biases/errors are so fundamental that they impede the use of the existing products in climate analysis.

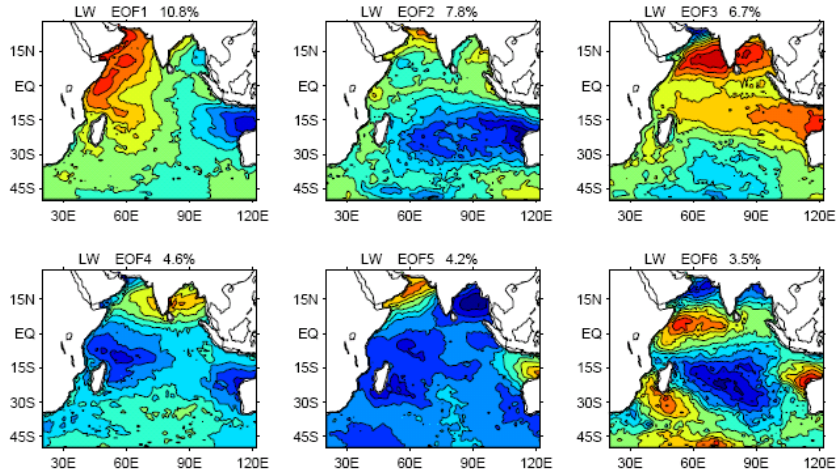
Reducing or eliminating the three errors is a difficult task, because the errors come from many sources. Effort in the past year has focused on reducing the gap effect on short and longwave radiation estimates in the Indian Ocean and a linear smoothing technique was selected based on the error characteristics. EOF analysis was performed to check the signals before and after smoothing (Figures 4-5). It is clear that the smoothing effectively removed the gap and meanwhile does not alter the signals.



### Before (SRB Original)



### After (SRB smoothed)



**Figure 5.** First 6 EOF patterns for longwave radiation before (upper 6 panels) and after linear smoothing was applied (lower 6 panels).

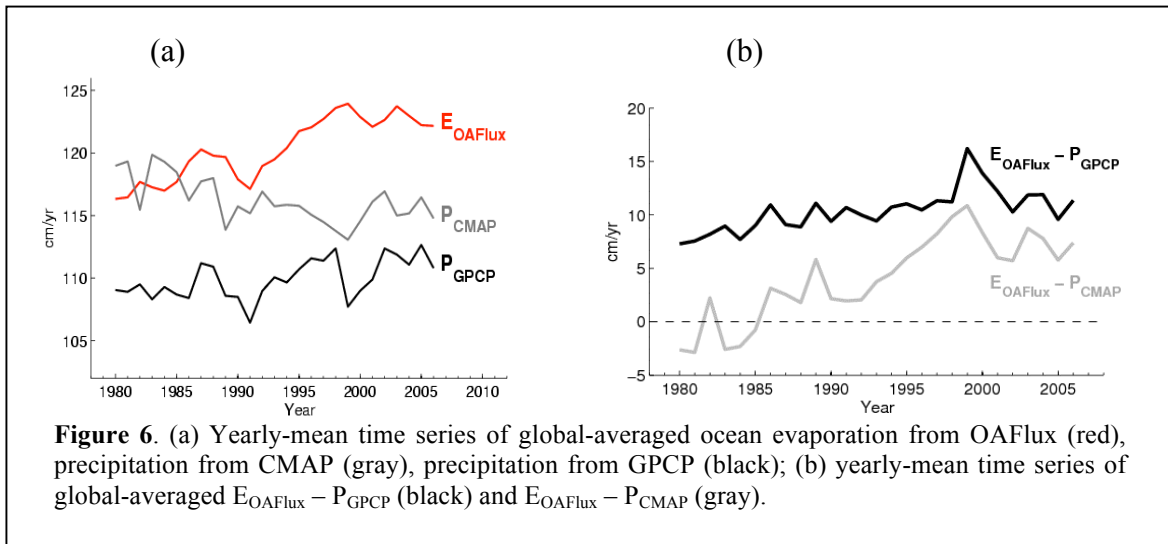
## 2.4. Connecting OAFlux evaporation product to precipitation products to study the change of global water cycle in past decades

The evaporation rate ( $E$ ) is linked to latent heat flux ( $Q_{LH}$ ) following the relation:  $E = Q_{LH}/(\rho L_e)$ , where  $\rho$  is the density of seawater and  $L_e$  the latent heat of vaporization. The relation is based on the fact that evaporation releases not only latent heat but also water vapor to the atmosphere. The relation also allows the global ocean evaporation to be computed by capitalizing on the availability of the ~50 year global analysis of latent heat flux. Thus, time series of monthly and daily analysis of ocean evaporation from 1958 to 2006 is developed and released online as a supplement to existing ocean heat flux products.

The OAFlux evaporation production provides the climate community the needed component in studying global water cycle. Precipitation estimates from 1979 to present are available from two groups, the NASA GPCP (Global Precipitation Climatology Project) and

NOAA CMAP (CPC Merged Analysis of Precipitation by Xie and Arkin). Hence, in addition to developing the evaporation dataset, the effort in the past year has made to link the OAFlux evaporation with GPCP and CMAP precipitation, and to analyze and understand changes in global water cycle from 1980 to the present, the period that precipitation datasets are available.

The OAFlux evaporation shows that global evaporation has been increasing steadily since the early 1980s (Figure 6a, red line), indicative of a changing global water cycle ([3] Yu 2007). Time series of global-averaged ocean precipitation from CMAP and GPCP do show precipitation has also been changing, but CMAP projects a downward trend opposite to the upward trend mapped by GPCP (Figure 6a, gray and dark black lines). The two different projections of the change of precipitation give different trends of evaporation-minus-precipitation (E-P, Figure 6.b). On one hand,  $E_{\text{OAFlux}} - P_{\text{GPCP}}$  suggests that global freshwater fluxes have increased only slightly, though both components show a large increase and thus an enhanced water cycle. On the other hand,  $E_{\text{OAFlux}} - P_{\text{CMAP}}$  suggests that precipitation has decreased with evaporation increasing, resulting in a large increase of freshwater fluxes to the atmosphere. The cause of the differences in the precipitation products is being investigated.



In summary, we have accomplished the following five major tasks in the past year:

- (i) Public release of OAFlux analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006.
- (ii) Construction of a flux validation database that constitutes flux buoy time series measurements at 100+ locations.
- (iii) Experimenting optimal approaches to improve estimates of shortwave and longwave radiation at the ocean surface.
- (iv) Connecting OAFlux evaporation product to precipitation products to study the change of global water cycle in past decades.
- (v) Lead and co-authored 10 referred manuscripts and 1 technical report.

### 3. PUBLICATIONS AND REPORTS

Yu, L., J. Xin, and R. A. Weller, 2008: Multidecade global flux datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, OAFlux Project Tech. Rep. OA-2008-01, 64 pp.

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Contributors to Levinson, D.H., J.H. Lawrimore, et al., 2008: State of the Climate in 2007. *Bulletin of the American Meteorological Society*, 89, S1–S179.